The Predictability of Large-Scale, Short-Period Ocean Variability in the Philippine Sea and the Influence of Such Variability on Long-Range Acoustic Propagation

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LONG-TERM GOALS

The long-term goal of this project is a complete and accurate understanding of the properties of acoustic pulses sent over mesoscale to global scales. In particular, I want to understand the forward problem for calculating travel times of the early ray arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals. The better the understanding of the forward problem, the better acoustic data can be used to understand the ocean.

OBJECTIVES

This work aims to develop models of ocean variability for understanding and predicting long-range acoustic propagation. Models of ocean variability, and therefore the associated sound speed variability, in the Philippine Sea are to be developed from historical data and from the PhilSea'09 and PhilSea'10 experiments, or adapted from existing efforts. Emphasis is placed on distinguishing between predictable (mesoscale, internal tides) and stochastic (internal waves) variabilities. These models will be used to obtain the relevant acoustic properties (e.g., full-depth sections of sound speed) such that the effects of variability on long-range acoustic propagation can be calculated and compared to field data. The work therefore aims to develop models for the physical oceanography of the central Philippine Sea with accurate and verified acoustical and oceanographic properties and with a quantified assessment of the predictability of the various model components.

APPROACH

The general approach to better understanding acoustic propagation is a careful processing and study of acoustic data obtained on line arrays of hydrophones from acoustic propagation of over 100-5000 km ranges, acquired as part of the larger North Pacific Acoustic Laboratory (NPAL) and Philippine Sea Experiment collaborations in the present case. These experiments have been conducted primarily by Peter Worcester and his group at the Scripps Institution of Oceanography. Long-range acoustic data are often analyzed in combination with other complementary in situ data that may be available, such as from thermistors or satellite altimetry. Regional or global ocean models have also been very useful in understanding the various influences on acoustic propagation. The general aim has been to use the acoustic data to test and improve such models, and such models do not resolve the ocean down to the internal waves scales that affect the acoustic propagation, however. If such models are data assimilating, then they provide an optimal synthesis of the available in situ data. This synthesis is usually better than can be obtained by considering the data in isolation. Indeed, the optimal test of

acoustic data, in situ data, and ocean models is through the combination of all these elements by data assimilation, which simultaneously tests the observations against the physical or acoustical model in a systematic and self-consistent way while reconciling the disparate data types. The modeling and state-estimates from the Estimating the Circulation and Climate of the Ocean (ECCO) group at the Jet Propulsion Laboratory have been used for these purposes; our collaborator with that group is Dimitris Menemenlis.

WORK COMPLETED

The past three years of this project have involved several activities and lines of research. The various facets of this project are summarized here.

Acoustic Thermometry of Ocean Climate. The paper describing a decade of acoustic thermometry in the North Pacific (1996-2006) and a comparison of those measurements to several numerical ocean models was completed. This paper was published in the Journal of Geophysical Research (Dushaw et al. 2009, see also Dushaw et al. 1999). Peter Worcester at the Scripps Institution of Oceanography was a close collaborator; there were other collaborators from the NPAL group.

The Time-Mean State of Ocean State Estimates and Long-Range Acoustic Propagation. In the course of the study comparing measured travel times to model predictions, it became apparent that in some cases the time-mean state of some ocean models is so erroneous as to give completely unphysical results for predicted time fronts. For that study, the time-mean of the troublesome models were replaced by that from the World Ocean Atlas (Antonov et al. 2006, Locarnini et al. 2006), under the assumption that even if the mean state of a model was erroneous, it still reasonably predicts ocean variability. The World Ocean Atlas has always produced time fronts that compare reasonably well with measured data, so it is conjectured that calculating and comparing acoustic patterns in the time mean of models can produce a reasonable zero-order test of model fidelity to the "true" state of the ocean (Dushaw et al. 2011a). Figure 1 gives a global comparison of the smoothed World Ocean Atlas with a more recent, higher resolution (¼ °), eddy-permitting implementation of the ECCO model. Figure 2 compares a measured time front from an acoustic path of 3515 km range with the equivalent time front calculated using the World Ocean Atlas.

The predicted and measured travel times on some of these long paths have proved to have a surprisingly large difference in travel time of about one second. This discrepancy has proved to be perplexing to this researcher, at least. The state estimates are constrained by considerable data, and the variations in their travel times over O(10-yr) intervals are not that large (Figure 3). Instrumental error has been ruled out. The present thoughts are that these large travel time discrepancies result from three contributions: (1) the ocean models have a small, but significant, bias in their time-mean states, perhaps as a result of insufficient available data for the abyssal ocean, (2) the ocean is variable, so travel times measured during the short O(1-yr) intervals of the 1990/2000 experiments may not be entirely representative, and (3) an O(0.2 m/s) error in the sound speed equation.

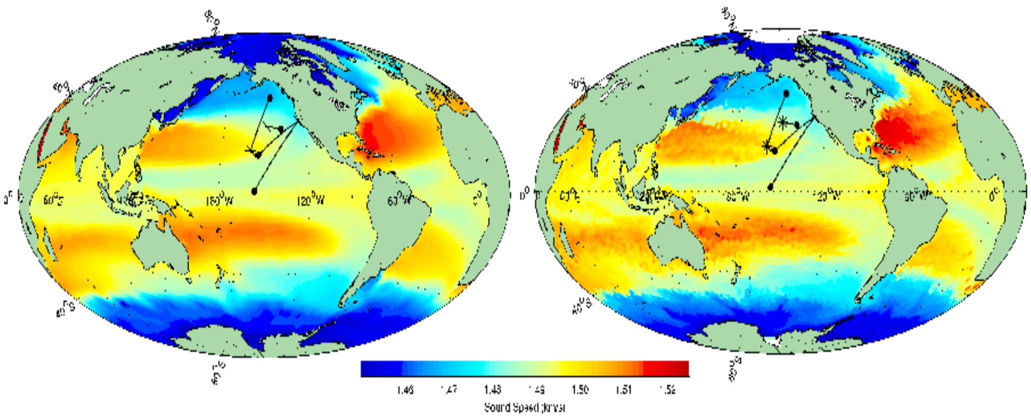

Figure 1 Two estimates for the state of the world's oceans. Sound speed at 300-m depth is shown, together with several acoustic paths over which acoustic measurements were made between 1995 and 2005. The left panel shows the highly smoothed realization of the 2005 World Ocean Atlas, while the right panel shows a snapshot derived from the eddy-permitting state estimates of the JPL ECCO2 program using the MITgcm. The overall acoustic properties calculated in the two realizations are very similar differing primarily in overall travel time, and secondarily in the dispersal of the arrival pattern.

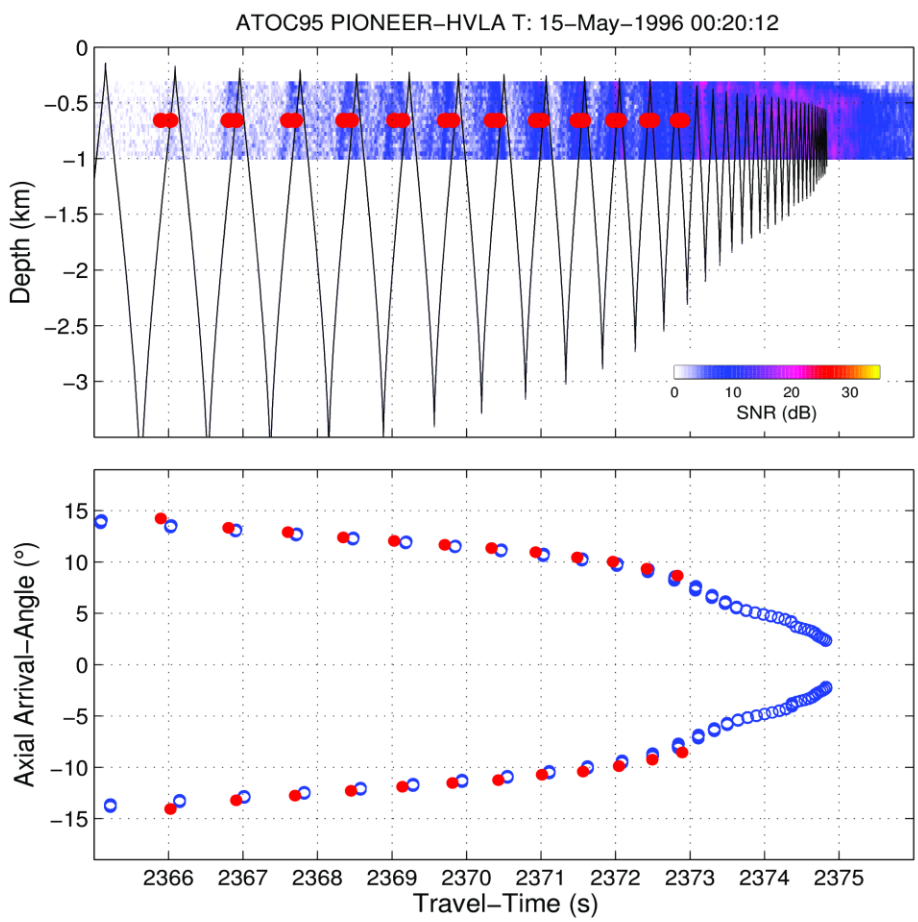

Figure 2 Top panel: The time front measured by the Hawaiian VLA from a transmission from Pioneer Seamount (3515 km range) on May 15, 1996 (colored intensity dB) compared to the time front calculated from the 2005 World Ocean Atlas (black lines). The measured and calculated absolute travel time and the dispersal of the arrival pattern in time closely correspond. A travel time offset of +0.3 s has been applied to the predictions to achieve the alignment. The red dots indicate the time mean travel times of the rays derived from the turning point filter (Dzieciuch et al. 2001). Travel time variations and changes to the dispersal of the pattern are usually small. Bottom panel: Comparison of measured (red dots) and predicted arrivals (blue circles) in arrival angle and travel time variables resulting from the turning point filter.

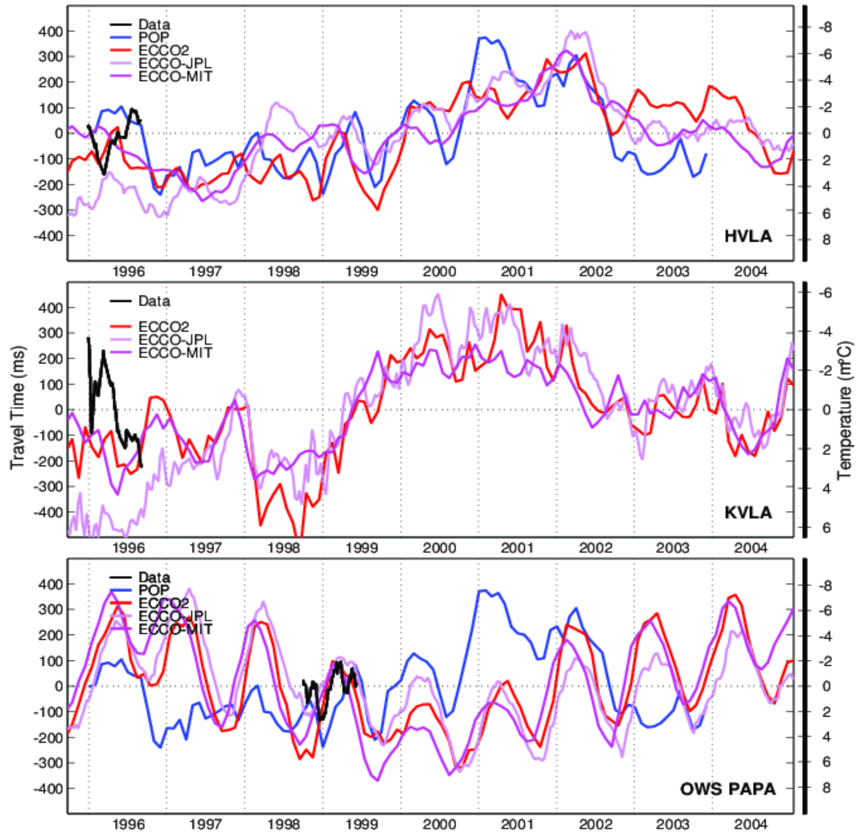

Figure 3 Travel time time series over a decade derived from several ocean models or state estimates for the three acoustic paths: Pioneer to KVLA, Pioneer to HVLA, and Kauai to OWSP. The state estimates agree generally, but differ substantially in detail. The black lines in each panel are time series measured during the ATOC program. To obtain travel times associated with measured arrivals, the time mean state of some models require correcting.

Participation in Philippine Sea '09 and '10 Deployment and Recovery Cruises. I participated in the test experiment in the western Philippine Sea (PhilSea'09) and I did a preliminary analysis of data acquired during that month-long experiment. This analysis guided the final design of the more extensive PhilSea'10 experiment. I similarly participated in the recovery of instrumentation of the PhilSea'10 experiment, and have been involved with the initial look at the extensive data collected, as described below. The PhilSea'09 and PhilSea'10 experiments were conducted by Peter Worcester at the Scripps Institution of Oceanography.

High-Resolution Numerical Ocean State Estimates for the Philippine Sea and Long-Range Acoustic Propagation. HYCOM and ECCO2 ocean model integrations were obtained for the region of the Philippine Sea (Figure 4). Both are high-resolution (1/4° or smaller) eddy-permitting models. ECCO2 is formally a "state estimate" in that it has been constrained by a variety of ocean data through data assimilation. Typically such models produce fields of depth, potential temperature, and salinity, from which pressure and sound speed can be calculated. The derivation of sound speed fields from these models, and subsequent acoustic propagation through them, is now routine (Figure 5). These fields capture such variability as the heave of the main thermocline with the passage of mesoscale features, and this variability is reflected in changes to the time fronts. These models form a background environment to which such things as internal tides, fronts, or internal waves could be added to form a more complete or realistic model for the acoustics of the region. One aim of this

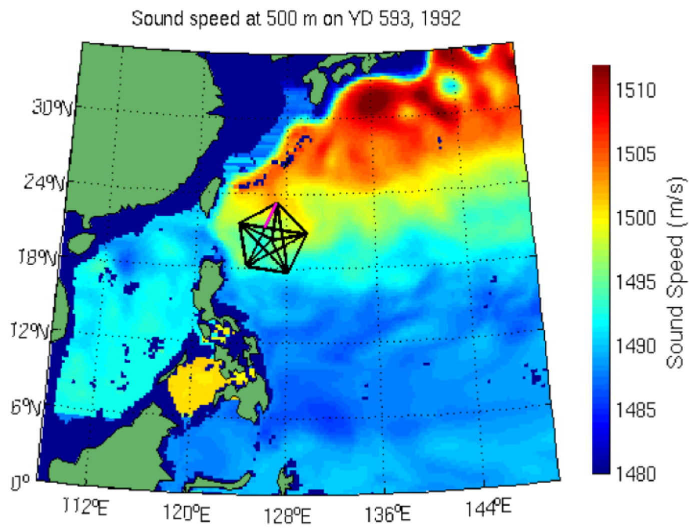

Figure 4 Sound speed derived from a state estimate for the Philippine Sea and the PhilSea ’09 (single magenta line) and ’10 (pentagonal array, black lines) tomography array. The T1 mooring was located at the northern point of the magenta line, while the DVLA mooring was located at the southern point, within the pentagonal array of PhilSea'11. The quantity shown is sound speed at 500 m depth. This snapshot shows the eddy-permitting state estimates of the JPL ECCO2 program using the MITgcm. Such snapshots are available at 3-day intervals.

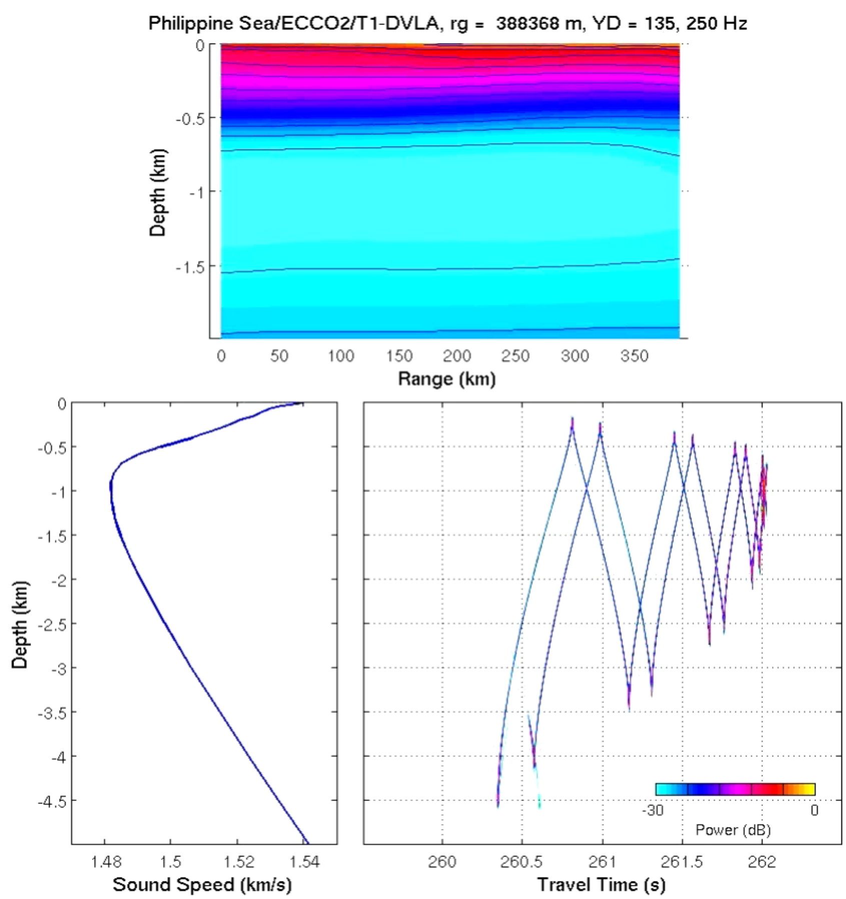

Figure 5 A sound speed section along an acoustic path between source T1 and receiver DVLA of PhilSea’09 derived from a state estimate for the Philippine Sea on a particular day (top) and the associated acoustic arrival pattern calculated using the RAM parabolic equation code, assuming a 250-Hz broadband acoustic source.

research is to assemble as complete an ensemble of such elements as possible, both predictable and stochastic, such that the resulting “grand” model accurately represents the acoustic environment over all scales.

Mapping the Internal Tides of the Philippine Sea Using Satellite Altimetry: Predictability and Effects on Acoustic Propagation. A remarkable result from the analysis of satellite altimeter data has showed that over much of the world’s oceans, the mode-1 internal tide is predictable, using harmonic constants derived for the major tidal constituents from satellite altimetry data (Dushaw et al. 2011b). Predictions from this analysis give predictions that match the RTE’87 (Dushaw et al. 1995), AMODE (Dushaw 2006), and HOME (Dushaw et al. 2011b) time series of acoustic travel time in both amplitude and phase, even though some of these time series were acquired 10-15 years prior to the availability of the altimeter data. These results suggest that the mode-1 internal tide of the Philippine Sea basin may be predictable. Initial attempts to predict these internal tides from the altimeter data are as yet problematic (Figure 6), however, suggesting that this region may be active and variable enough as to disrupt the internal tide coherence. These results are still preliminary, however, and work is continuing toward this predictability, or a better understanding of how the internal tide coherence is lost.

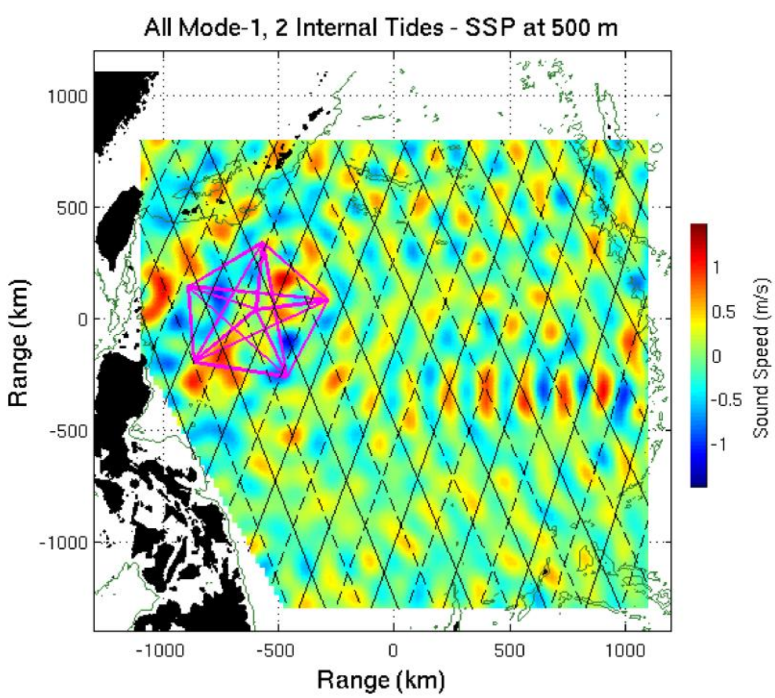

Figure 6 Snapshot of internal-tide sound speed variations at 500 m depth (all frequencies, all wavenumbers) for the region of the PhilSea’10 experiment. Solid and dashed lines indicate tracks of of the TOPEX/Poseidon altimeter. The tidal field is confused as a result of the interference of multiple wavenumbers (See Dushaw et al. 2011b). This region appears to be problematic for predicting the travel time variations of internal tides, but more work is needed to understand why, if true, that seems to be the case.

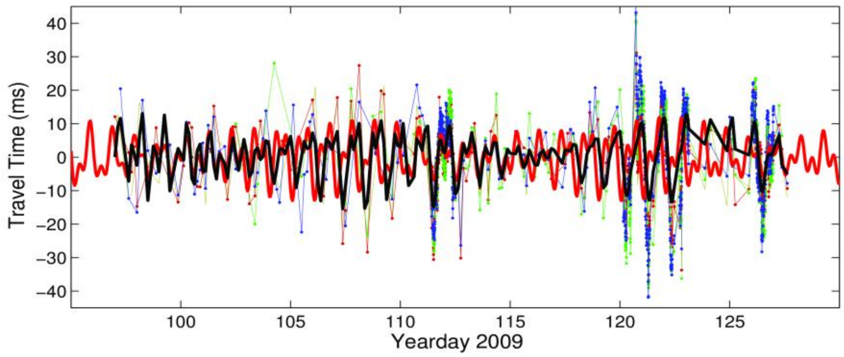

Figure 7 A comparison of travel time series derived from the T1-DVLA acoustic path of the 2009 pilot experiment (black) to travel times predicted by a tidal analysis of altimetry data (red) for the mode-1 internal tide. The individual ray travel time time series are indicated by the thin lines. The preliminary tidal prediction does not agree very well with the measurements in detail, but it does capture the spring-neap variations.

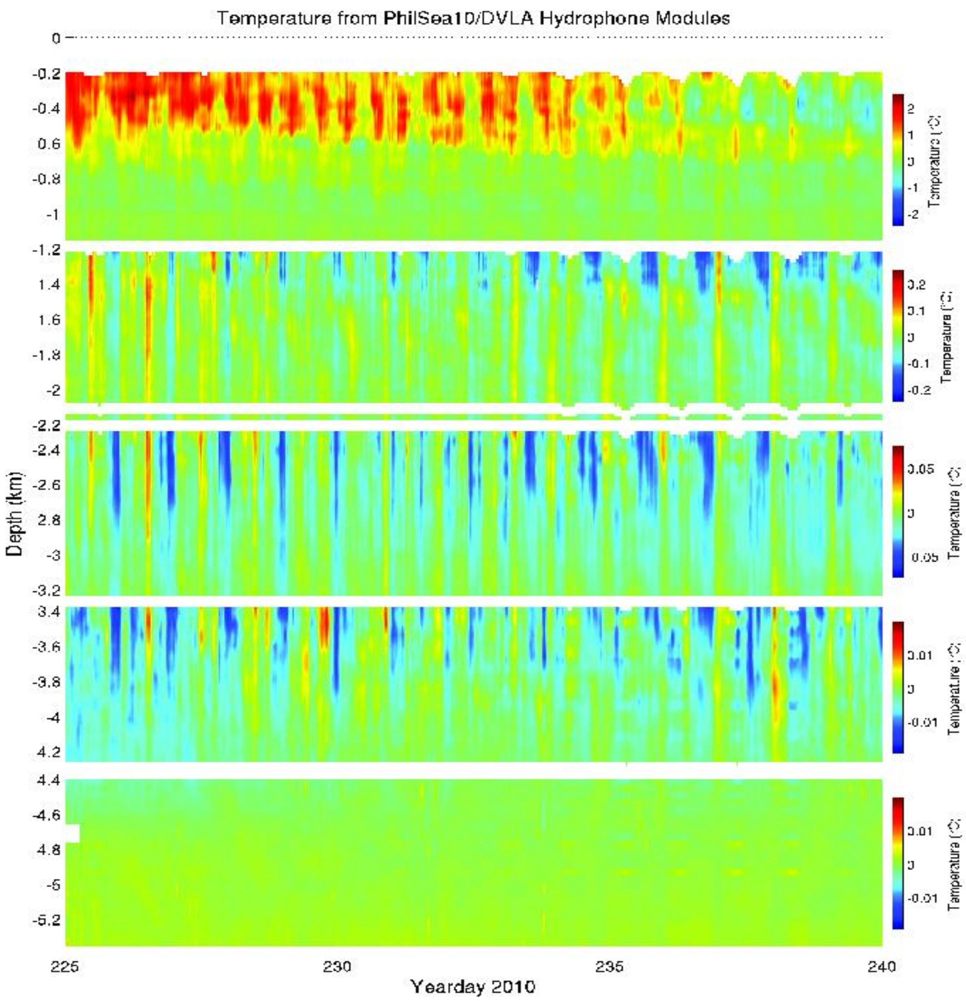

Figure 8 A preliminary look at fifteen days of thermistor data acquired on the PhilSea'10 DVLA, recovered in early April 2011. The mean temperature profile has been subtracted from these data. Each time series was acquired on a hydrophone on subarrays of the DVLA. The DVLA consisted of five such arrays, as indicated by the five panels. These time series have been roughly corrected for the pull-down of the mooring driven by ocean variability, and empirically corrected for the self-warming of the hydrophone elements. The 15-day interval of these data shows obvious signatures of internal-tide variations, one of the dominant signals in these data. The tidal variations span much of the DVLA array depths, hence indicate low-mode interal tides.

PhilSea’09 and '10 Thermistor and Tomography Data. During PhilSea’09, dense sampling of the water column by thermistors was obtained on both the acoustic source mooring (T1) and receiver mooring (DVLA). John Colosi of the Naval Postgraduate School acquired these data. This data set provided excellent measurements of the vigorous tidal variability of the Philippine Sea, allowing separation of the tidal variability into both tidal constituent and modal components. The analysis follows that of Dushaw et al. (2005). At least over the month-long duration of this experiment, the mode-1 internal tides measured by the thermistors were coherent, with 90% of the variance accounted for by a simple tidal analysis. In situ data such as thermistors and tomography (Figure 7) provide an excellent in situ test of the predictability of the low-mode internal tides.

Internal tides observed by thermistors during the 2009 pilot experiment and preliminary data acquired during the year-long PhilSea10 experiment show that the internal tides are a ubiquitous and dominant signal. Of this variability, mode 1 is not only the largest component, but also the most predictable. Low-mode variations are apparent in the 2010 DVLA thermistor data (Figure 8), as is apparent by the tidal variations that extend almost throughout the water column. With these thermistor data, and other such data collected on the other PhilSea10 moorings, the expected analysis will be to separate the mode components of variability and then to quantitatively assess the temporal coherence of the mode variations. Based on the 2009 results so far, it is likely that mode-1 variations, at least, will have high temporal coherence. The goal of the ongoing research is then to assess quite how temporally coherent the low-mode internal tides are, and the extent to which these variations can be predicted empirically from the analysis of altimeter data, or by the numerical modeling of these waves by modeling programs such as that by Brian Powell (with Colette Kerry) at the University of Hawaii.

A comprehensive analysis and synthesis of the PhilSea'10 data is just getting underway.

OceanObs’09/Acoustics in the Ocean Observing System. A "Community White Paper" was developed as an advocacy document for the implementation of acoustic remote sensing capabilities, both passive and active, in the Ocean Observing System. This paper was a contribution to the international OceanObs’09 conference held in Venice, Italy in September 2009 (Dushaw et al. 2010; http://www.oceanobs09.net). An international collaboration was brought together for this purpose (see the author list of Dushaw et al. 2010), and a "Special Plenary Session" focused on acoustic applications for ocean observation was organized and given during this conference (Figure 9). This work was an explicit goal of this grant.

RESULTS

Main conclusions of the decade-long program of acoustic thermometry in the eastern North Pacific (ATOC) were: (a) No obvious indication of climate change was measured during this decade, but no such change was expected either in the eastern North Pacific. Inter-annual variability was surprisingly large, however. And (b), although the modern state estimates are data assimilating, incorporating all available data types such as altimetry and Argo profiling floats, these estimates were not capable of reproducing the acoustic time series. The implication of this conclusion is that the acoustic data provide valuable information about the state of the ocean at the largest scales that is not available by other means.

The original motivation for the work with the time-mean state of ocean models was that acoustical predictions using some of the models proved to be incapable of reproducing the expected or measured time front. Such gross disagreement means that measured and predicted ray arrivals cannot be identified, so that any tomographic inverse is entirely non-linear. Such models required a correction to

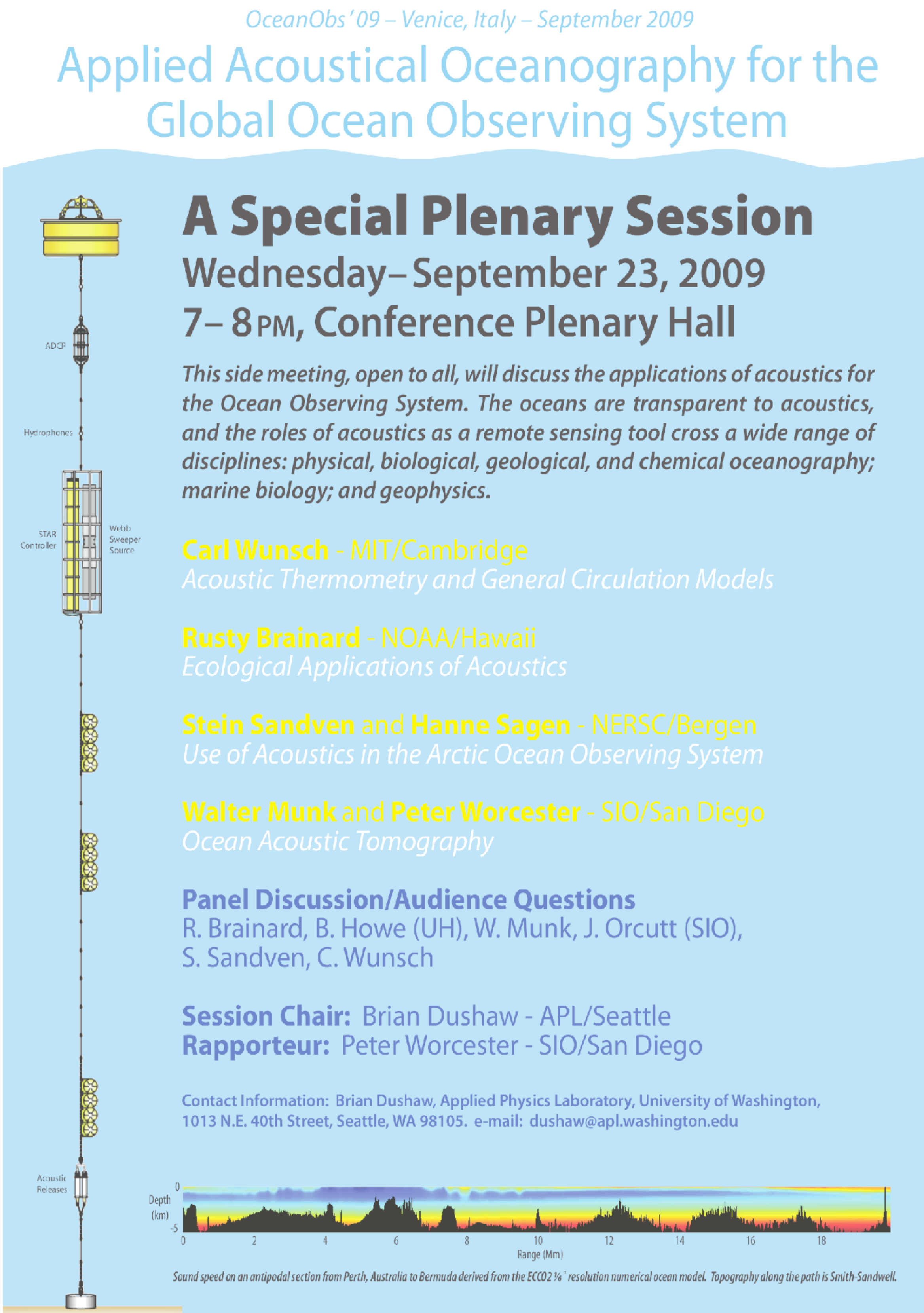

Figure 9 The poster used to advertise acoustics for the Ocean Observing System during OceanObs'09.

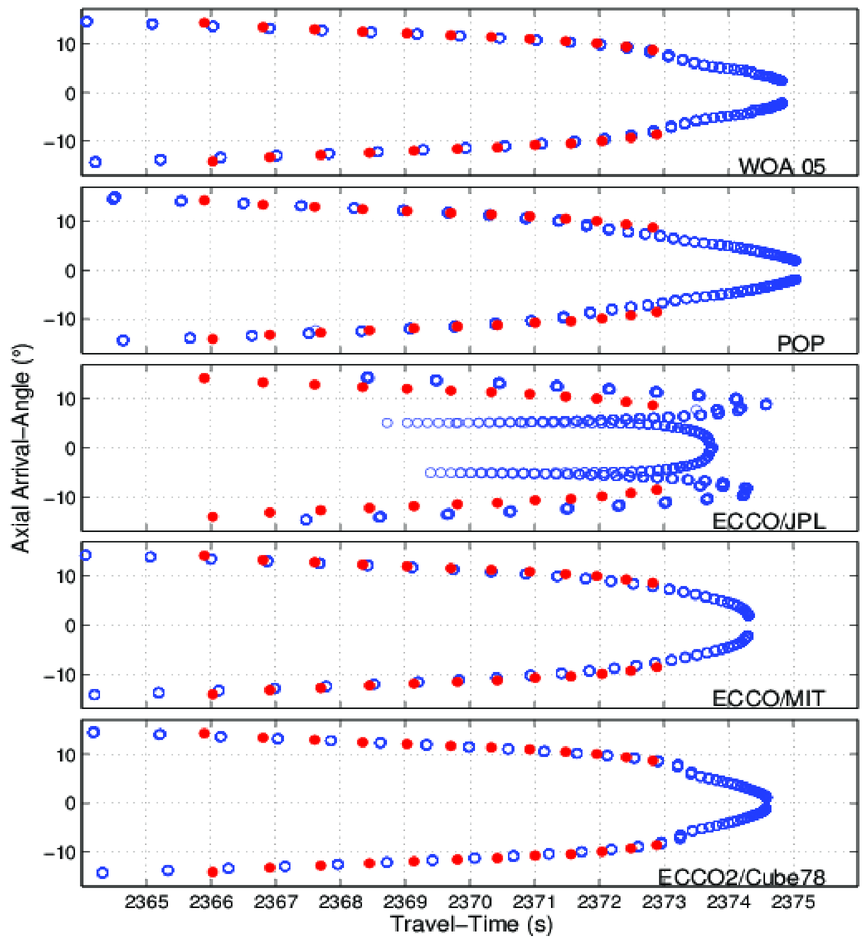

Figure 10 Turning-point filter predictions for the Pioneer to HVLA acoustic arrivals derived from the several models for the ocean state as indicated in the lower-right of each panel. Red circles are ray arrivals measured during the ATOC'95 experiment, while blue circles are the ray predictions. The time-mean of the model or state estimate were obtained to calculate these predictions. Some models for the ocean very poorly represent the mean state of the ocean which leads to poor, obviously incorrect, predictions for the arrival pattern. There is no physical justification for models that give such a poor representation for the mean ocean. The correspondence between the measurements and the predictions for the more recent models is unambiguous.

their time-mean state, with the assumption that their time-variability was reasonable, even if their mean state was not (Dushaw et al. 2009); this assumption has been shown to be correct. The more recent state estimates do not appear to have this problem, and they give time fronts that are very similar to those of the World Ocean Atlas (Figure 10). Today's ocean modeling capabilities are good enough that ocean acoustic tomography, coupled with these models as the prior state, presents a simple linear inverse problem.

Analysis of the data collected during PhilSea'09 and PhilSea'10 is still ongoing, hence definitive results cannot yet be stated. It appears that the mode-1 internal tides of the region, including semidiurnal and diurnal constituents, are vigorous and highly coherent in time. Some degree of predictability is indicated from the comparisons of the in situ observations with the altimetry analysis, but the precise nature of this predictability is not yet clear. We are working toward the capability of accurate

predictions of both the amplitude and phase of the mode-1 internal tides over much of the Philippine Sea basin, much like the barotropic tide is predicted now.

IMPACT/APPLICATIONS

The conclusions with respect to acoustic thermometry indicate a transformative development for the world's ocean observing system. While the Argo profiling float system and satellite altimetry programs are at present the cornerstone of this global observing system, it is clear that the acoustical observations will be a valuable complementary addition to these elements, giving new insights into the nature of subsurface variability of the ocean at the largest scales. It is also clear that these disparate data types can be synthesized in an objective, systematic way through data assimilation into ocean models. The latest ocean models have sufficiently realistic acoustical properties that they offer reasonable zero-order reference states for ocean acoustic tomography. There are no technical or theoretical impediments to implementing acoustic thermometry as part of the ocean observing systems. The present system of observations and modeling aims not only to understand ocean variability, but also to predict this variability over a variety of time scales; thermometry will be an important addition to the system for achieving these goals.

The ability to predict the variations of mode-1 internal tides is a novel concept in physical oceanography; never before have any variations of internal waves of the ocean been seen as predictable. The precise nature of this predictability and how it may be employed for scientific research or other applications are as yet unclear, but this capability will no doubt be transformative.

RELATED PROJECTS

This project has been a contribution to the North Pacific Acoustic Laboratory (NPAL) collaboration, which comprises researchers from the Applied Physics Laboratory, the Scripps Institution of Oceanography, and the Massachusetts Institute of Technology, among others. (http://npal.ucsd.edu/)

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HONORS/AWARDS

From 2011-2012 Brian Dushaw will be a Fulbright Scholar at the Nansen Environmental and Remote Sensing Center (NERSC), University of Bergen, Bergen, Norway, engaged on the project: “Acoustical Applications for an Arctic Ocean Observing System”

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14. ABSTRACT
As part of a large, ongoing collaborative effort aimed at understanding long-range acoustic propagation in the ocean, this project seeks to understand the forward problem for calculating travel times of the early ray arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals. The better the understanding of the forward problem, the better acoustic data can be used to understand the ocean. Areas of focus were the central North Pacific Ocean and the Philippine Sea. Models of ocean variability for understanding and predicting long-range acoustic propagation were developed. Data obtained from the decade-long ATOC/NPAL project in the Pacific were used to better understand acoustic propagation over megameter distances and to measure the large-scale thermal variability of the eastern Pacific basin. Models of mesoscale and internal tide variability in the Philippine Sea were employed or developed to compute travel time variations for comparison to thermistor and acoustic data obtained in 2009.

15. SUBJECT TERMS
ocean acoustics, tomography, acoustic thermometry, internal tides, ocean observing system

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